Primer on Superconducting Radiofrequency Cavities

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Apologia

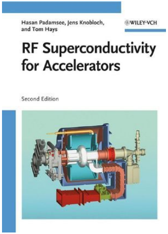
There is far too much material here than can be covered in a 30-minute talk. For more, you can refer to:

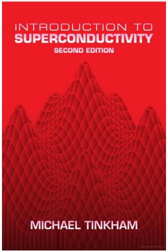
- the US Particle Accelerator School's course material:

  `http://uspas.fnal.gov`

- *RF Superconductivity for Accelerators* by Padamsee, Knobloch, and Hays, Wiley-VCH, 2008; and
- *Introduction to Superconductivity* by M. Tinkham, Dover, 2004.

Furthermore, this audience is very diverse. My talk will be completely new to some of you and old news to others.





Overview

- The basics
- Superconducting RF for accelerators
- What do we mean when we talk about films?
- "The Real World": Fabrication & challenges

1. The Basics

Basic phenomenology and the London equations

Start with a two-fluid model for conduction electrons: $n = n_s + n_n$.
Drude-Lorentz electron motion in a metal:

$$m\left(\dot{\mathbf{v}} + \mathbf{v}/\tau\right) = e\mathbf{E}.$$

$\tau \to \infty$ for a perfect conductor. $\mathbf{J_s} = n_s e\mathbf{v}$, so

$$\mathbf{E} = \frac{\partial}{\partial t}\left(\frac{m}{n_s e^2}\mathbf{J_s}\right). \tag{1}$$

Taking the curl,

$$\mathbf{h} = -c\nabla \times \left(\frac{m}{n_s e^2}\mathbf{J_s}\right). \tag{2}$$

And combining (2) with Ohm's law gives

$$\nabla^2\mathbf{h} = \frac{1}{\lambda^2}\mathbf{h}.$$

This is a description of the Meissner effect.

$$\nabla^2 \mathbf{h} = \frac{1}{\lambda^2} \mathbf{h}$$

so external fields are screened from the superconductor as

$$h(z) = h_{\mathrm{ext}} e^{-z/\lambda}$$

for 1D, anyway. Empirically,

$$\lambda(T) \approx \frac{\lambda(T=0)}{\sqrt{1-(T/T_c)^4}}.$$

Of course, the London equations are not the whole story.

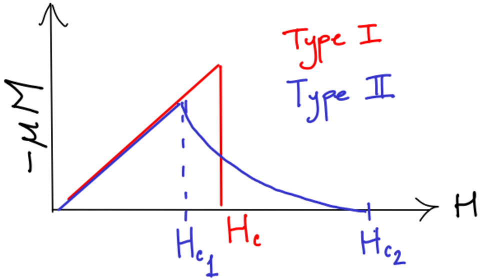
How to explain the *phase transition*?

- $C = T\frac{\partial S}{\partial T}$
- Discontinuity in C at critical temperature, characteristic of a secord-order phase transition.

"Isotope effect" suggests the lattice structure matters.

- E. Maxwell, "Superconductivity of the isotopes of tin", Phys. Rev. **86**, 235 (1952).
- $M^{0.5}T_c = \mathrm{constant}.$

Type-I vs Type-II Superconductors



- $0 < H < H_{c1}$: Meissner state
- $H_{c1} < H < H_{c2}$: vortex / Abrikosov state

2. SRF for Accelerators

Why SRF for accelerators?

Normal-conducting surface resistance

$$R_s = \sqrt{\frac{\mu_0 \omega}{2\sigma}}$$

- $\sigma_{\mathrm{Cu}} \approx 5.8 \times 10^7$ S/m
- Pick $f = 1.3$ GHz
- $R_s \sim 10$ mΩ
- Removing MW of dissipated power from Cu structures is a difficult problem at CW!

Superconducting surface resistance (Nb)

$$R_s \approx 2 \times 10^{-4} \left(\frac{f\,[\mathrm{MHz}]}{1500} \right)^2 \frac{1}{T} e^{-17.7/T} + R_{\mathrm{res}}$$

- $R_{\mathrm{res}} \sim 10^{-8}\ \Omega$ for niobium
- $R_s \sim 10^{-6}\ \Omega$
- Much less dissipative than Cu, of course.
- SRF is efficient, even when accounting for LHe refrigeration.

Why Nb for SRF?

Consider *elemental* superconductors.

Material	T_{c} (K)	H_c (mT)	H_{c1} (mT)	H_{c2} (mT)
Pb	7.2	80	n/a	n/a
Nb	9.2	200	170	400

- Nb has highest T_c and H_{c1} of the elemental superconductors.
- It has a relatively low H_{c2}.
- It is readily available in bulk and *formable*.

3. Superconductivity in Films

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- Compound superconductors may have higher T_c, H_{c1}, etc. MgB_2, e.g., is not available in bulk for traditional cavity forming, machining.
- Cu is cheaper by an order of magnitude.

Thermodynamic critical field in bulk vs. film

- Ginzburg-Landau theory (coupled, nonlinear PDEs) describes pseudowavefunction ψ describing SC charge carrier density.
- Appropriate gauge choice (London gauge, $A_{\parallel} = \int_0^x h(x')dx' \approx Hx$) and thin-film boundary conditions ($d < \lambda$, etc.) yields Gibbs free energy $G(|\phi|^2)$.
- Punchline:

$$H_{c\parallel} = \sqrt{24} H_c \frac{\lambda}{d}$$

4. “The Real World”: Fabrication & Challenges

How thin is too thin?

For $d < \lambda$, Ginzburg-Landau gives

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So *on paper* you can "win" by minimizing d. In practice, and especially on large surfaces, you will encounter problems with film adhesion and uniformity.

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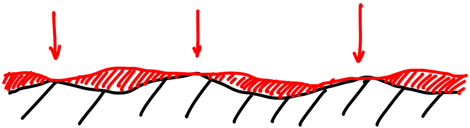
Adhesion: Film/substrate interface must be managed carefully.

Uniformity: Lattice mismatch, internal stress relieved as grains grow. "Pinholes" are also a concern:



Magnetron sputtering: prior art

G. Cavallari *et al.*, “Superconducting cavities for the LEP energy upgrade”, Proc. PAC’93, Washington DC, 1993.

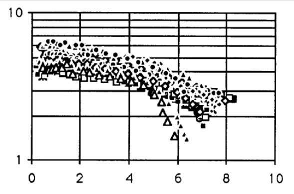


Figure : $Q_0/10^9$ vs E_{acc} (MV/m), bulk Nb.

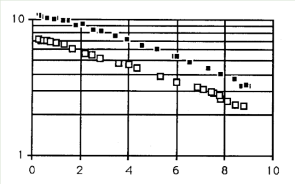


Figure : $Q_0/10^9$ vs E_{acc} (MV/m), Nb on Cu (best & worst).

- 352 MHz, elliptical SRF cavities
- Spec to vendor: $Q_0 \geq 4 \times 10^9$ at 6 MV/m.
- Goal to reduce material costs, improve conductivity to LHe bath.

Magnetron sputtering: current challenges

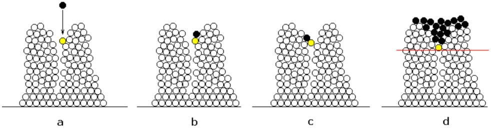


Figure : G. Wu *et al.*, "Energetic deposition in vacuum", 10th Workshop on RF Superconductivity, 2001, Tsukuba, Japan.

- Adatom mobility is limited. Cu substrates cannot be heated to temperatures that would help Nb mobility.
- Low adatom mobility $\rightarrow$ columnar films. Defects more likely.
- Process gas can be trapped in film, introducing impurities.

High-energy film deposition

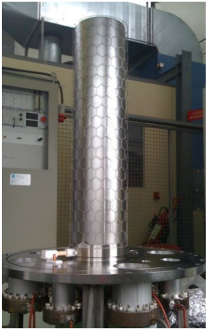
Film quality can be improved by adding energy to adatoms.

- Bias sputtering
- Plasma arc
- Electron-cyclotron resonance
- High-power impulse magnetron sputtering

Note also a distinction between energetic *condensation* (for improved surface mobility) and energetic *deposition* (to implant film material under the substrate surface).

Bias sputtering

Insert grids between cathode & anode, bias to control incident ion energy.



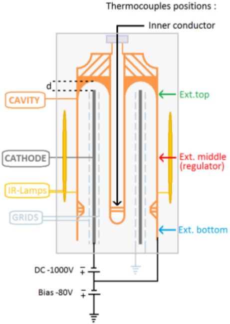


Figure : W. Venturini Delsolaro, Proc. SRF2013, Paris, France 2013.

Quarter-wave resonators for HIE-ISOLDE coated (Nb/Cu) via bias sputtering.

Cathodic arc deposition

- Plasma forms at "cathode spots" (non-stationary, high current density).
- Vacuum arc discharge permits UHV base pressures.
- Biasing grid + substrate allows some control over ion energies, angle of incidence on substrate.

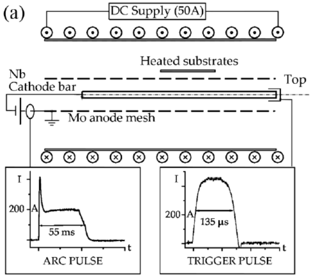
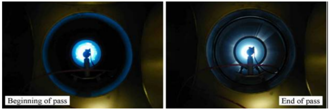


Figure : M. Krishnan, PRST-AB **15**, 032001 (2012).



Electron-cyclotron resonance

- How can we eliminate process gas from energetic deposition?
- Nb neutrals generated via e-beam evaporation (system operates in high vacuum)
- Waveguide supplies RF
- Electrons in strong field undergo energetic cyclotron motion, ionizing Nb neutrals.
- Deposition energy $\sim$ 100 eV.

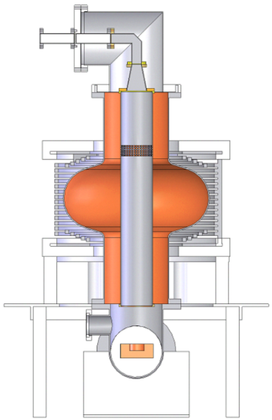


Figure : A.-M. Valente *et al.*, Proc. EPAC 2004, Lucerne, Switzerland.

High-power impulse magnetron sputtering (HiPIMS)

- Power at magnetron surface is *pulsed* to achieve much higher power densities than conventional DC magnetron sputtering.
- Duty factor $\sim 1\%$.
- Much higher ion concentrations; the high power density allows for self-sputtering.

A. Anders *et al.*, Proc. SRF2011, Chicago IL.

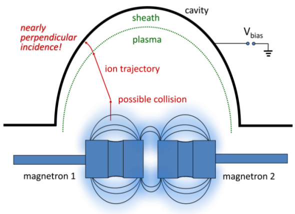
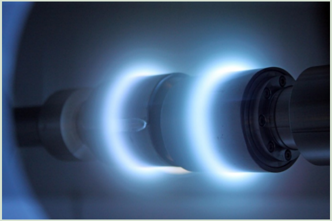
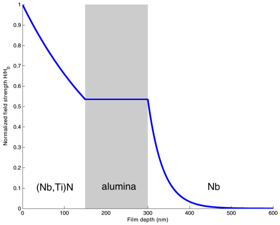
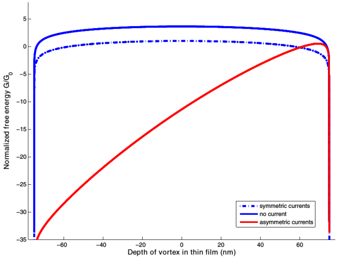


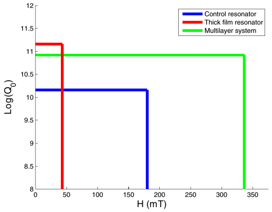
Figure 6: Schematic of a dual magnetron setup: here, the cavity can be biased and the sheath can be used to control the ion energy and ion impact angle.



A. Gurevich, Appl. Phys. Lett. **88**, 1 (2006).





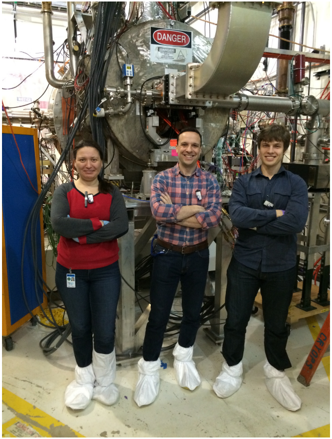


- Multilayers screen bulk from applied B
- Vortex free energy modified, increases H_{c1}.
- I grabbed these plots from my thesis. His original paper may be more clear.

Limitations of this approach

- Thick films have a *lower* free energy gradient than thin films of equivalent material.
- Increasing layers starts to create problems with thermal conductivity.
- Sam Posen's talk (next) will also address this.

frame



We have some experience at Fermilab with RF in strong magnetic fields.

- Contact me any time for more information. You also have some local experts to contact.